



# Thermal Design of Vapor Cooling of Flight Vehicle Structures using LH2 Boil-off

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08-03-2015



# Outline

- **Background of the vapor cooling using LH2 boil-off**
- **Vapor cooling concept considered for SLS EUS forward skirt**
- **1D thermal model to investigate**
  - ✓ **size of the cooling tube**
  - ✓ **number of the cooling tubes**
  - ✓ **entire or partial length of the skirt to be cooled**
- **3D thermal model prediction of vapor cooling performance**
  - ✓ **Four configurations**
    - a. **One spiral cooling tube with 3 turns covering the entire skirt**
    - b. **One spiral cooling tube with 2 turns covering 25% of the skirt length**
    - c. **Two spiral tubes with one turn each covering 25% of the skirt length**
    - d. **Axial cooling tubes (16) covering 25% of the skirt length**
  - ✓ **Two scenarios**
    - **on ground (steady-state)**
    - **5 day lunar mission (transient)**
- **Conclusions**



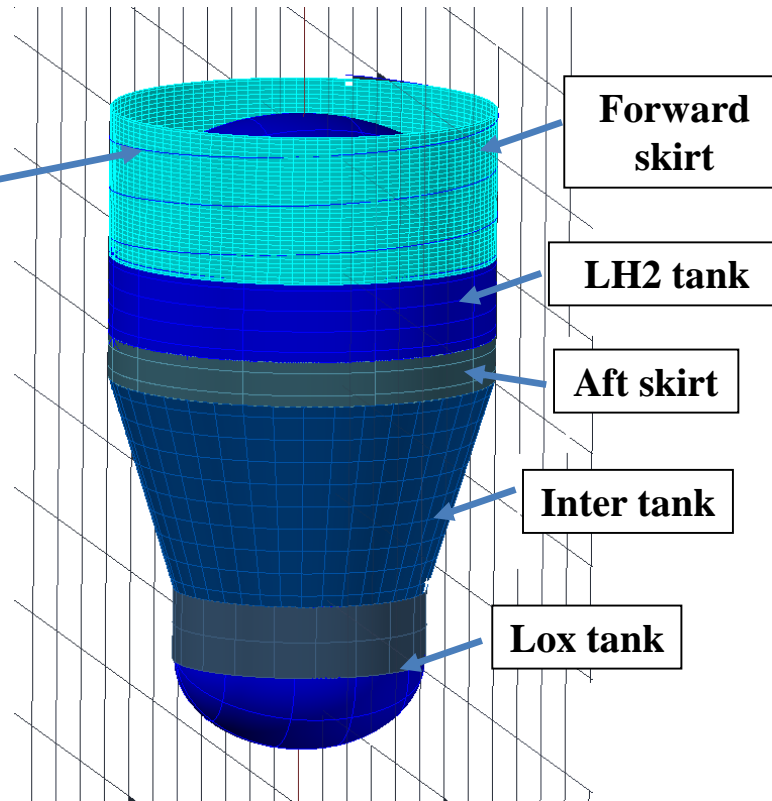
# Background

- **Using LH2 boil-off vapor to cool the flight vehicle upper stage structure can**
  - ✓ **Reduce heat leak to the LH2 tank**
  - ✓ **Lower the boiling-off rate such that saving mass of propellant and extending the life of the stage**
  - ✓ **Heat up the vented gas for other purpose as a heat source (tank settling)**
- **In theory, the heat leaking into LH2 tank from the structure will be reduced with the boil-off vapor cooling on the structure**
- **However, the amount of heat leak reduction depends on**
  - ✓ **The amount of boil-off vapor is available**
  - ✓ **The total heat load on the structure**
  - ✓ **Vapor cooling configurations**



# Vapor cooling concept

**Cooling loop  
on forward skirt**

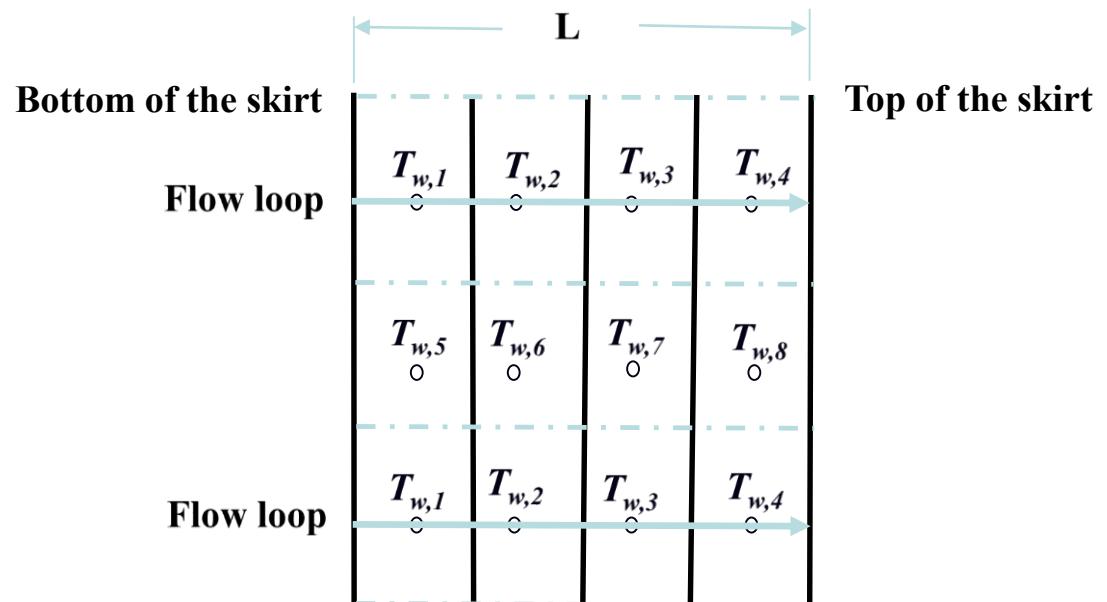
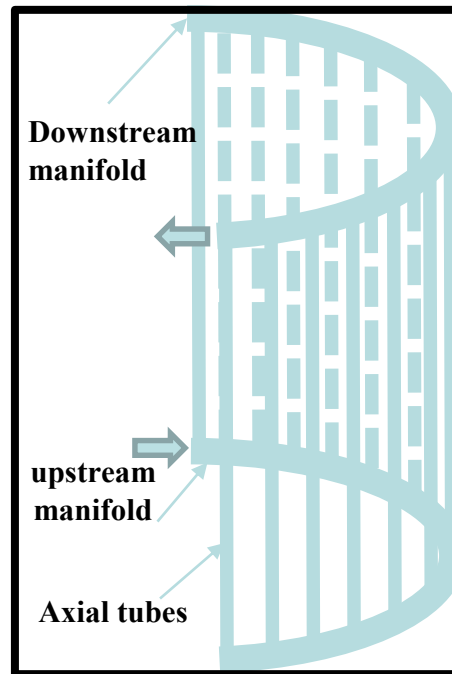


**Space launch system (SLS)  
Exploration Upper Stage(EUS)**



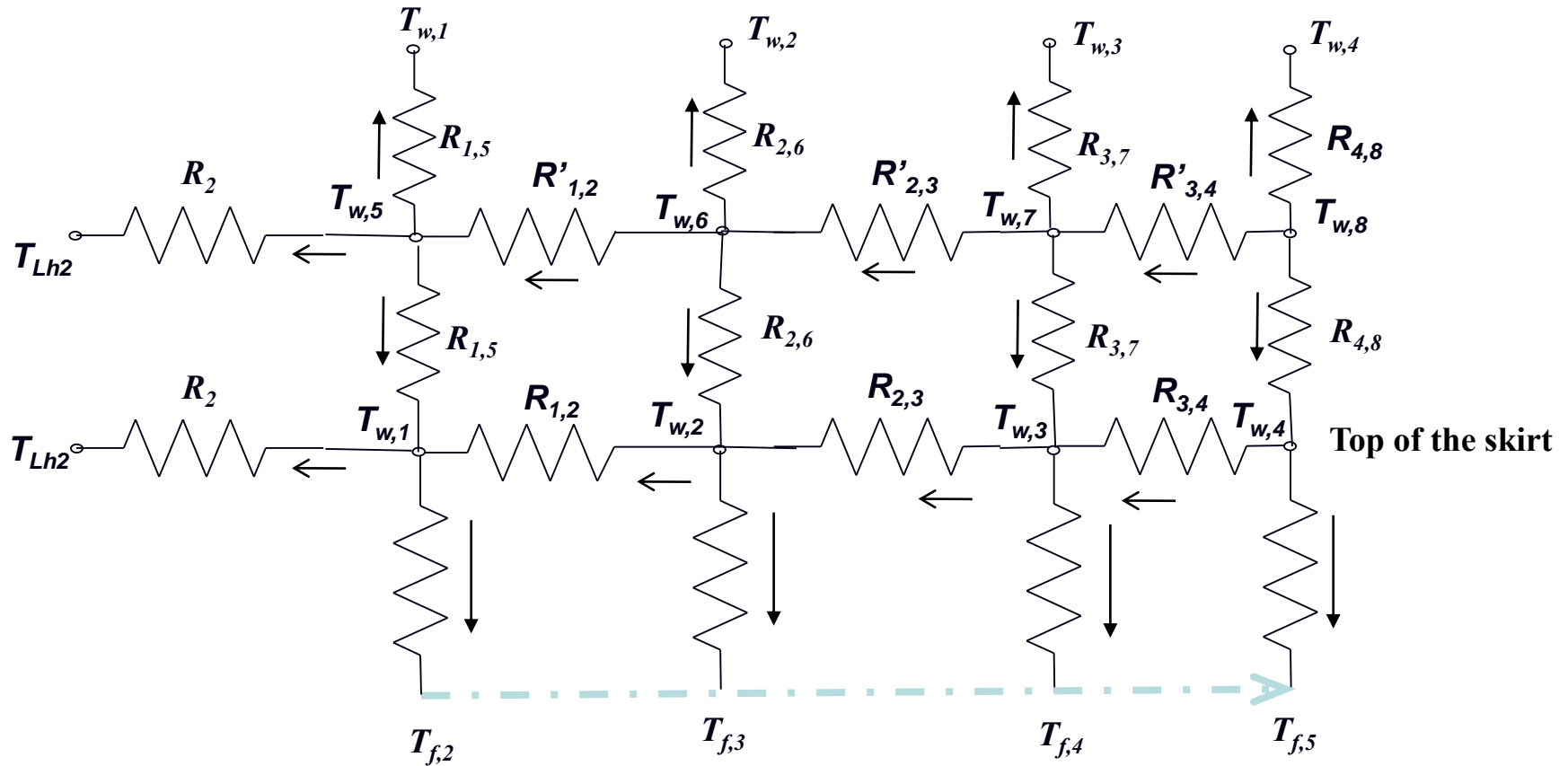
# 1D analysis

- **Vapor cooling configuration:**
  - ✓ Upstream and downstream manifolds + axial tubes
  - ✓ Provides uniform cooling to the skirt in the circumferential direction
- **Need to investigate:**
  - ✓ Number of cooling tubes along axial direction (8,16,32, 64)
  - ✓ Length of the skirt to be cooled (100%, 75%, 50%, 25%)
  - ✓ Size of the cooling tubes (ID = 3/4",3/8",1/8")
- **Build a 1D thermal model (4 nodes along the entire skirt length)**





# 1D thermal circuit for tubing along axial direction

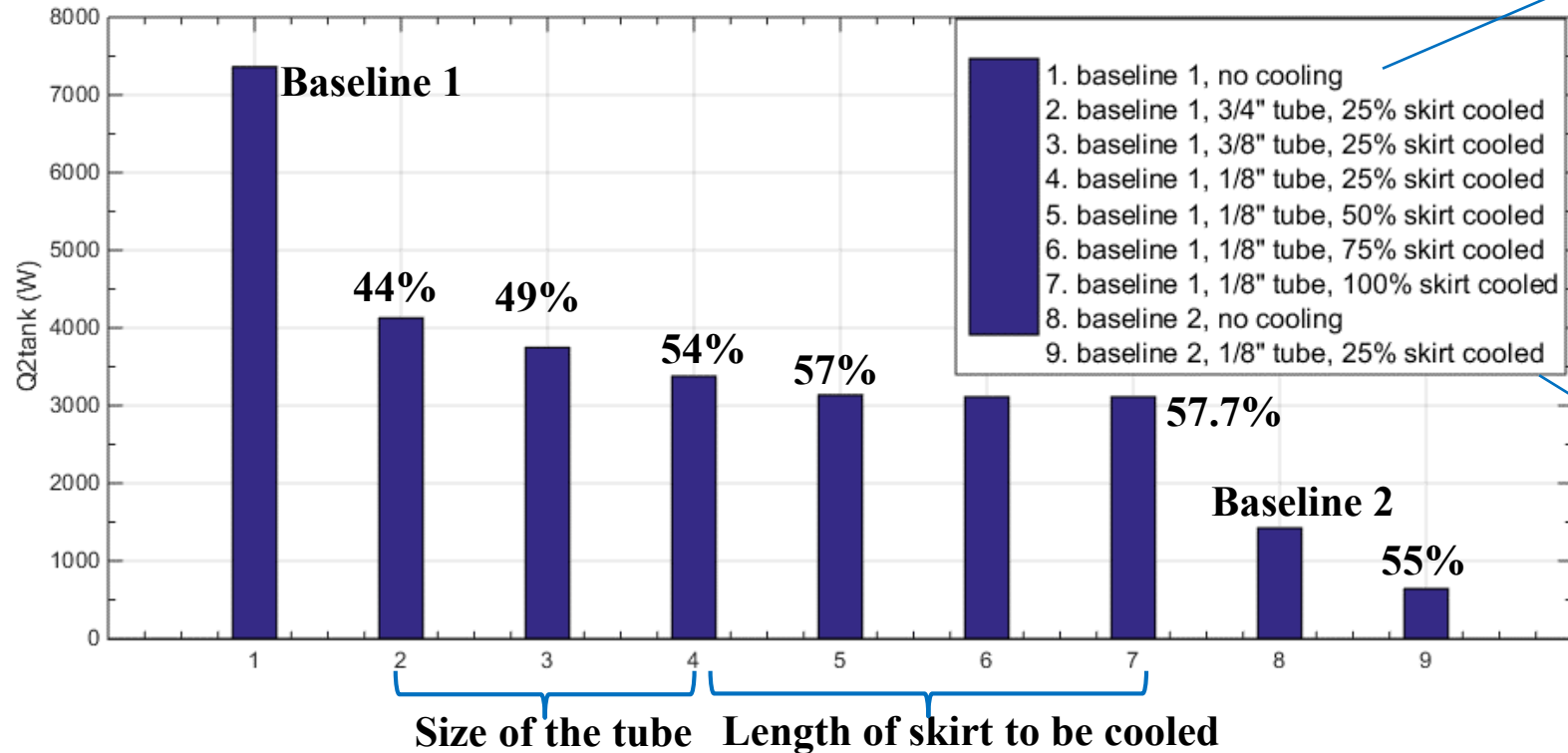


$R_{1,2}$ ,  $R_{2,3}$  and  $R_{3,4}$ : conduction resistance,  $R_2$ : contact resistance



## 1D thermal model results for axial tubing (16 tubes)

1. Baseline 1: no insulation on the skirt, top of the skirt: adiabatic
2. Baseline 2: insulate the skirt, top of the skirt:  $T = 300$  K
3. Ambient:  $T_a = 300$  K, radiation only



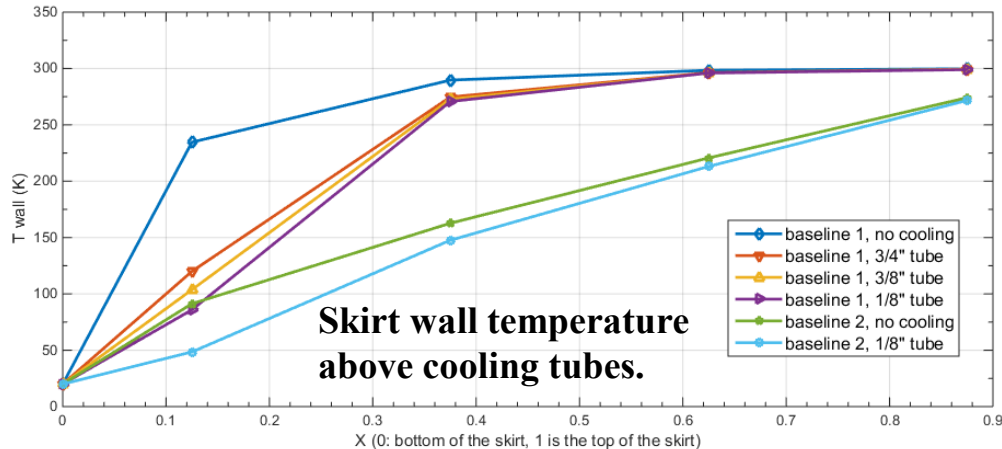
Q2tank (W)	Heat leak reduction
7360	0
4127	44%
3747	49%
3377	54%
3135	57%
3112	57.7%
3112	57.7%
1422	0
640	55%

- Cooling the 25% of the skirt from the bottom is almost as effective as cooling the entire skirt.
- Using smaller tubing (1/8" diameter) provides less heat to the tank with higher pressure drop.
- Insulating the skirt will reduce significant heat leaking into the tank.



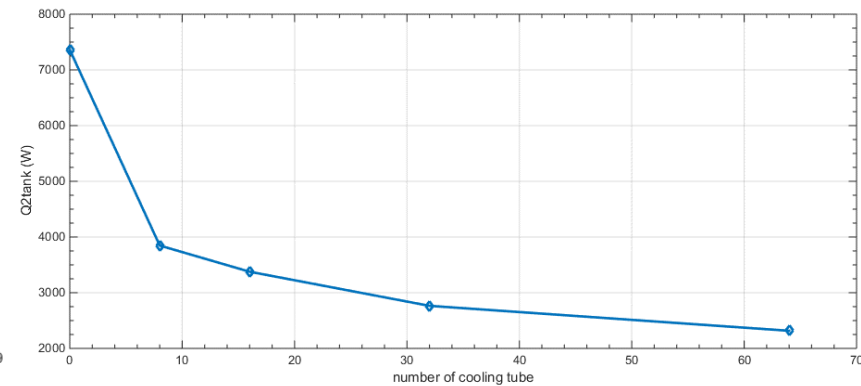
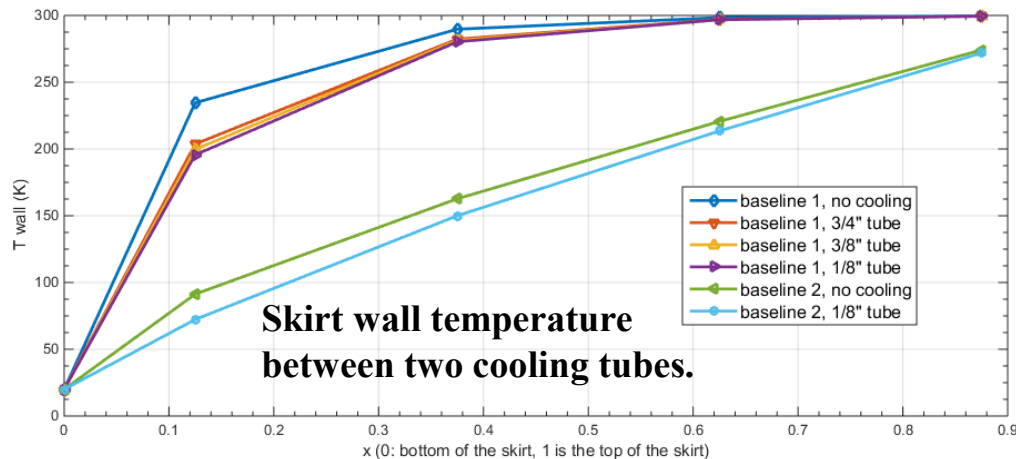
# 1D analysis results

(25% of skirt length is cooled, 16 tubes)



(1/8" diameter tube, cool 25% of the skirt length)

No. of cooling tubes	Total Q2tank (W)	Heat reduction
0	7360	0
8	3847	47.7%
16	3377	54.1%
32	2765	62.4%
64	2317	68.5%







# 1D analysis results

## Sensitivity study of the contact resistance between skirt and tank ( $R_2$ )

1/8" tube, 16 tubes, 25% skirt cooled	1500 w/m <sup>2</sup> -k	3000 w/m <sup>2</sup> -k	6000 w/m <sup>2</sup> -k
Q2tank (W) (no cooling)	6776	7360	7680
Q2tank (W) (cooling)	3185.6	3377.7	3491.2
Heat leak reduction	53%	54%	54.5%

## Different size of skirt/tank

1/8" tube, 16 tubes, 25% skirt cooled	Half diameter, half length	Baseline 1	Half diameter, same length
Q2tank (W) (no cooling)	2700.8	7360	2186
Q2tank (W) (cooling)	1209.6	3377.7	947.2
Heat leak reduction	55.2%	54.1%	56.7%

## Different sink temperature

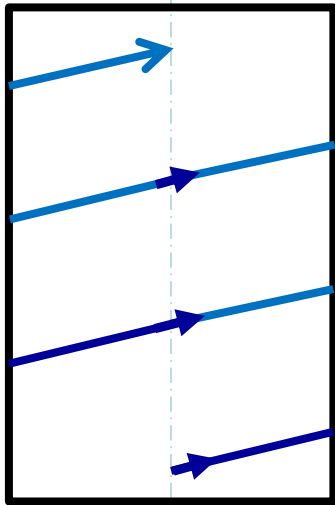
1/8" tube, 16 tubes, 25% skirt cooled	Ta = 300 K	Ta = 200 K	Ta = 100 K
Q2tank (W) (no cooling)	7360	2640	345.6
Q2tank (W) (cooling)	3377.7	1215	184.8
Heat leak reduction	54.1%	54%	46.5%

- Roughly similar percentage of heat leak reduction to LH2 tank for different size of skirt (length or diameter)
- Vapor cooling is more effective when ambient is warmer.

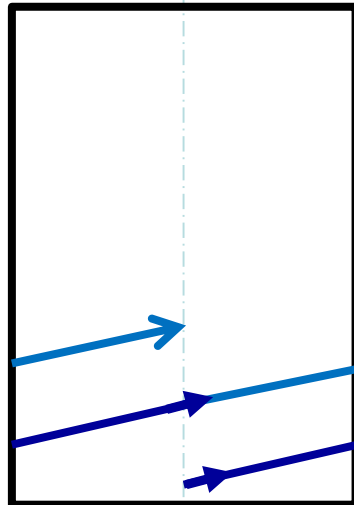
# 3D thermal modeling using Thermal Desktop (TD):

## Vapor cooling configurations:

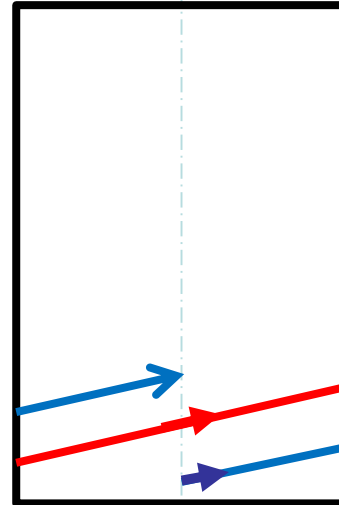
- ✓ Tubing along the circumferential direction (spiral, (a), (b), (c))
- ✓ Tubing along the axial direction (d)



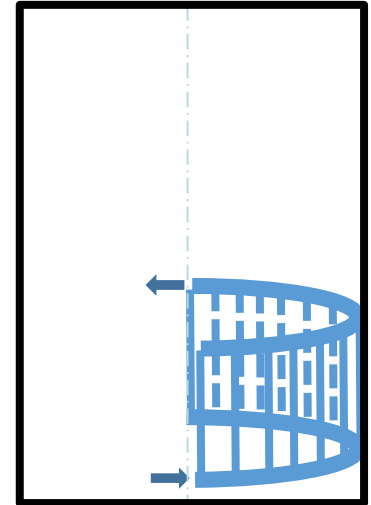
(a) 1 loop with 3 turns,  
on entire skirt



(b) 1 loop, 2 turns,  
on 25% of skirt  
length



(c) 2 loops, 1 turn/per loop,  
on 25% of skirt length

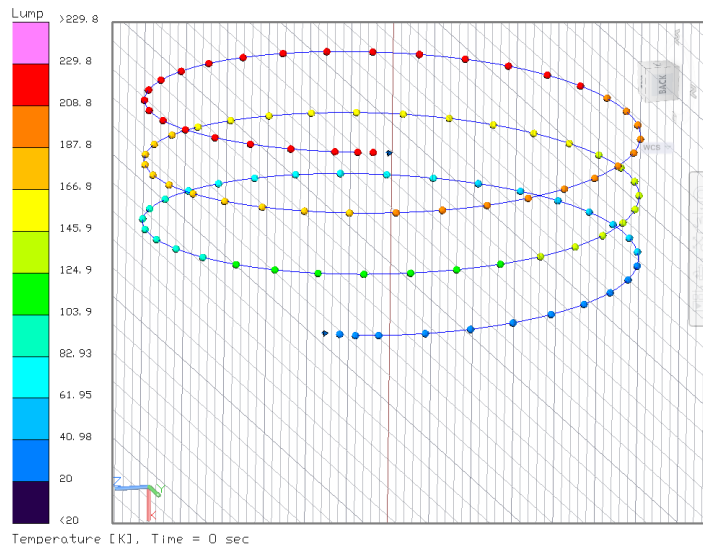
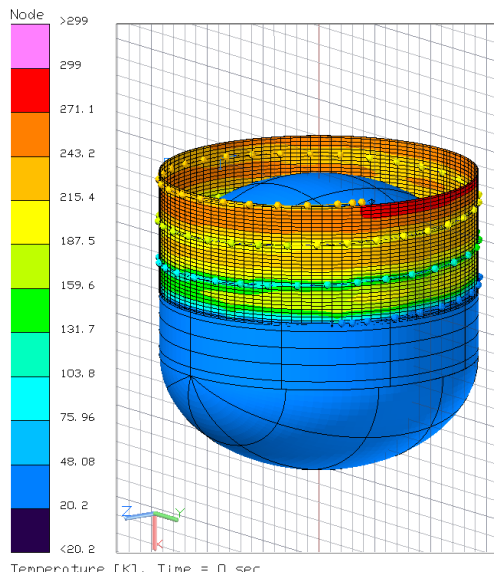


(d) Tubing along  
the axial direction,  
on 25% of skirt  
length

- Tube size: ID = 0.824", OD = 1.05"
- Tube material: Al 2219-T6
- Tube starts at 8.5" from the bottom of the skirt



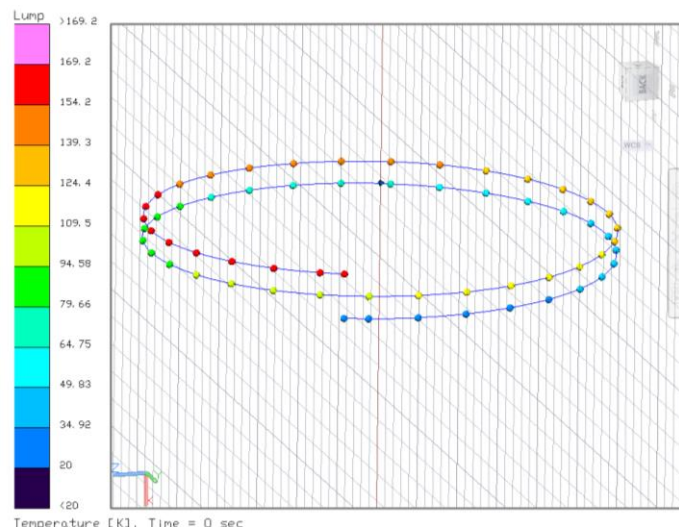
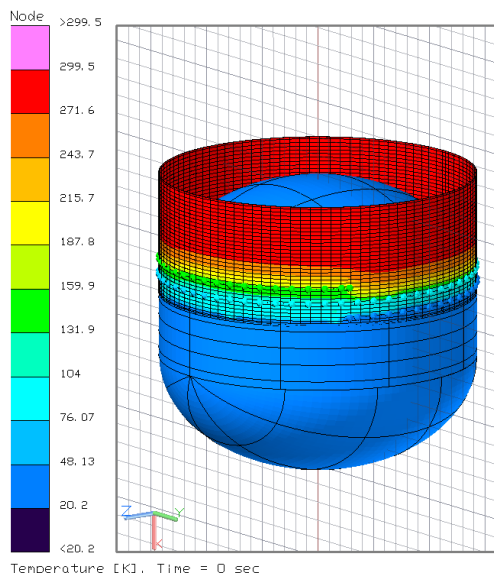
# 3D analysis results



✓ No cooling loop:  
 $Q_{2\text{tank}} = 8013 \text{ W}$   
from forward skirt

**Option A, one spiral tube covers the entire skirt**

Vapor mass flow rate (kg/s)	$Q_{2\text{tank}}$ (W)	$Q_{2\text{fluid}}$ (W)
0.008	3627.7	23711

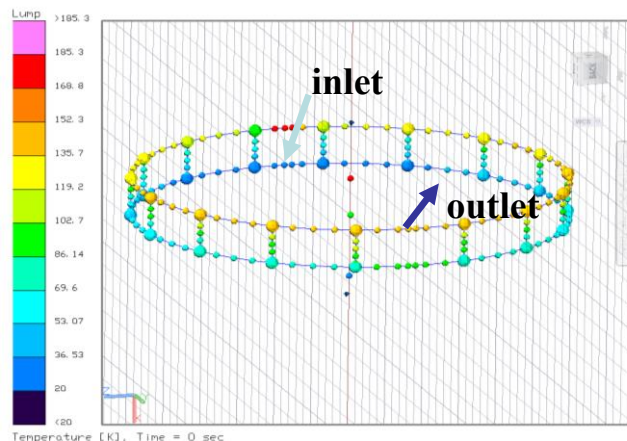
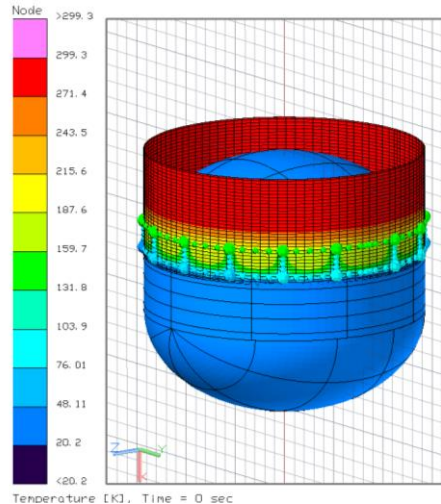
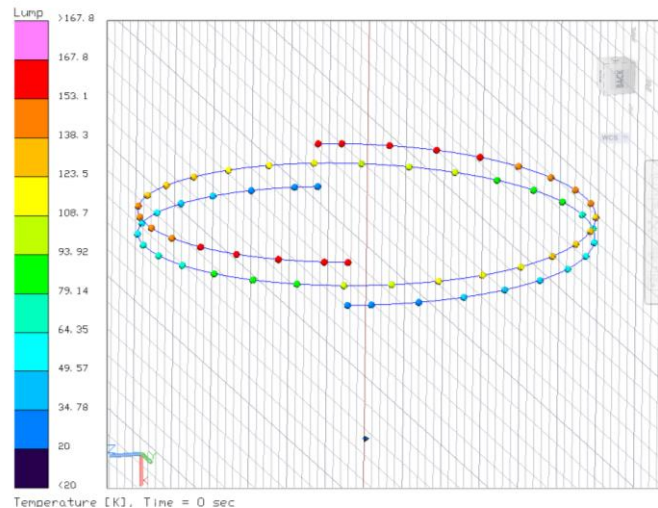
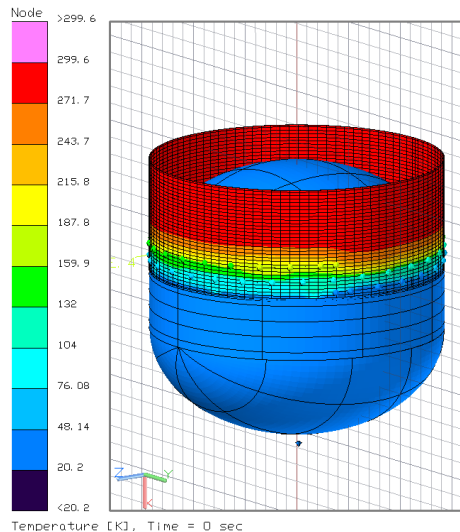


**Option B, one spiral tube (2 turns) cover 25% of the skirt length**

Vapor mass flow rate (kg/s)	$Q_{2\text{tank}}$ (W)	$Q_{2\text{fluid}}$ (W)
0.008	2346	12803
0.006	2665.6	11884



# 3D analysis results



**1D model prediction: mass flow rate: 0.00786 kg/s, Q2tank = 3377 W  
(16 vertical tube of 1/8" ID covers 25% of the skirt length, no manifold)**

**Option C, two spiral tubes (1 turn)  
cover 25% of the skirt length**

Vapor mass flow rate (kg/s)	Q2tank (W)	Q2fluid (W)
0.008	2449	12638
0.006	2817	11665

**Option D: two manifolds + 16 vertical tubes, cover 25% of the skirt length  
(manifold: ID = 0.824", OD = 1.05"  
Vertical tube: ID = 0.269", OD = 0.405")**

Vapor mass flow rate (kg/s)	Q2tank (W)	Q2fluid (W)
0.008	3058	12960
0.007	3362	12335

**(manifold: ID = 0.493", OD = 0.675",  
Vertical tube: ID = 0.125")**

Vapor mass flow rate (kg/s)	Q2tank (W)	Q2fluid (W)
0.008	2944	13348
0.007	3230	12743



# Summary of the 3D TD results

	tube size: ID = 0.824" OD = 1.05"					
Configuration	Vapor mfr (kg/s)	Q2tank (W)	Q2fluid (W)	Pdrop (psi)	Texit (K)	Heat leak reduction
A	0.008	3627.7	23711	11.8	229.8	59.7%
B	0.006	2665.6	11884	3.35	169.1	66.7%
C	0.006	2817	11665	0.14	167.8	64.8%
D	0.007	3362	12335	0.89	185.3	58%

	tube size: ID = 0.493", OD = 0.675"					
Configuration	Vapor mfr (kg/s)	Q2tank (W)	Q2fluid (W)	Pdrop (psi)	Texit (K)	Heat leak reduction
A	0.008	3732.6	23666	64.8	226.2	53.4%
B	0.006	2663.5	12849	28.7	144.1*	66.8%
C	0.006	2785	11714	6.5	169.0	65.2%
D	0.007	3230	12743	8.0	196.3	59.7%

- **Configurations B and C results in the least heat to the LH2 tank.** (\* convergence problem)
- **Tube size of 0.5" ID will have much higher pressure drop.**
- **For the tube along the axial direction, more vertical tubes are necessary if heat leak to LH2 needs to be further reduced.**



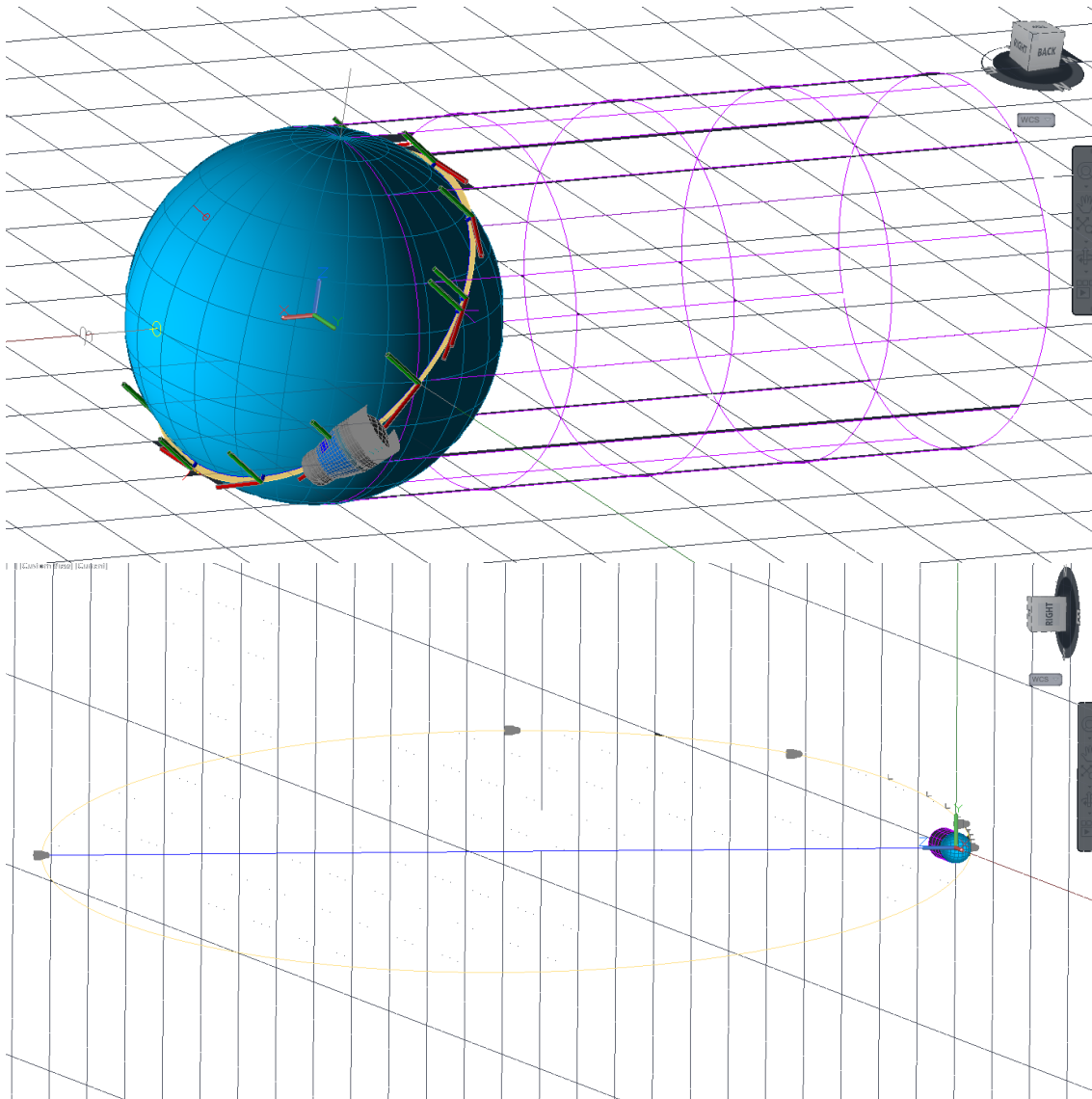
# 3D transient analysis

- **5 day lunar mission is considered for vapor cooling configuration performance**
  - **Lunar orbit rendezvous (lander)**
    - **On ground: 300 K sink temperature**
    - **Low Earth Orbit (LEO): 3 hr (2 orbits)**
    - **Trans lunar Cruise (TLC): 5 days**
      - **Nose to Sun**
      - **Broadside to Sun**
      - **Broadside to Sun with spin**





# LEO and TLC orbits

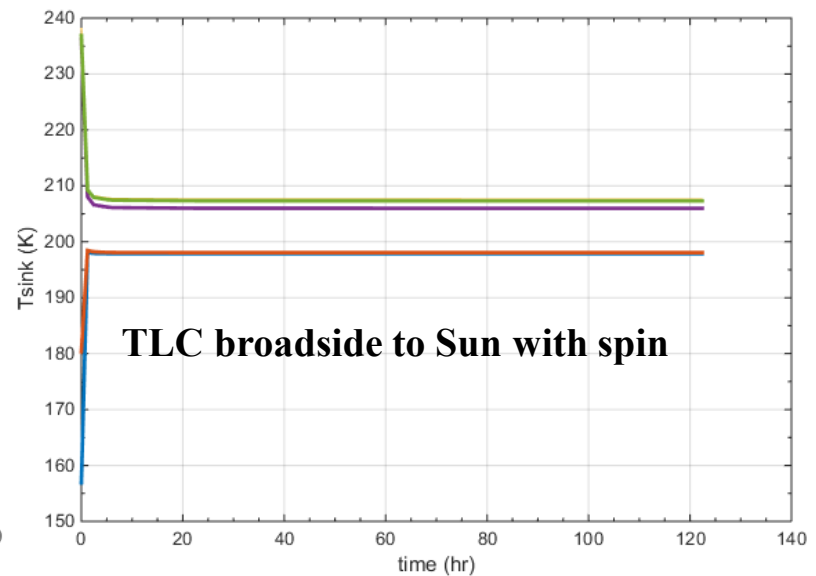
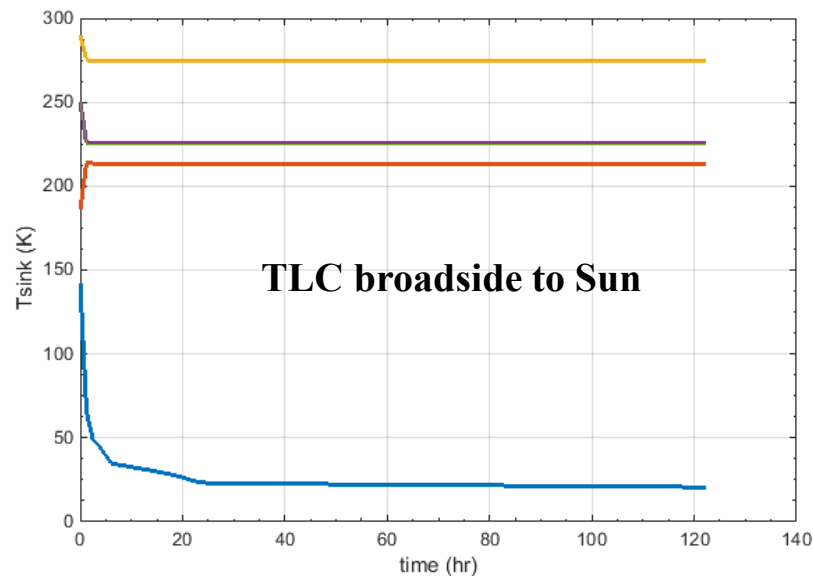
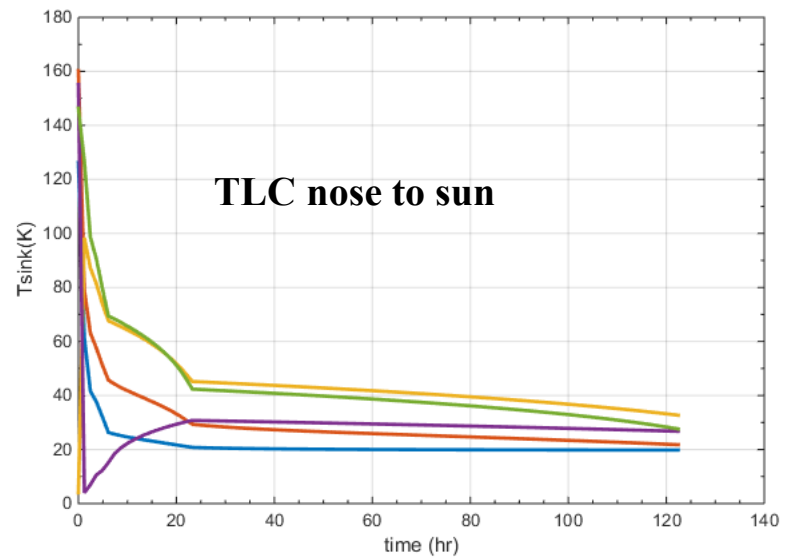
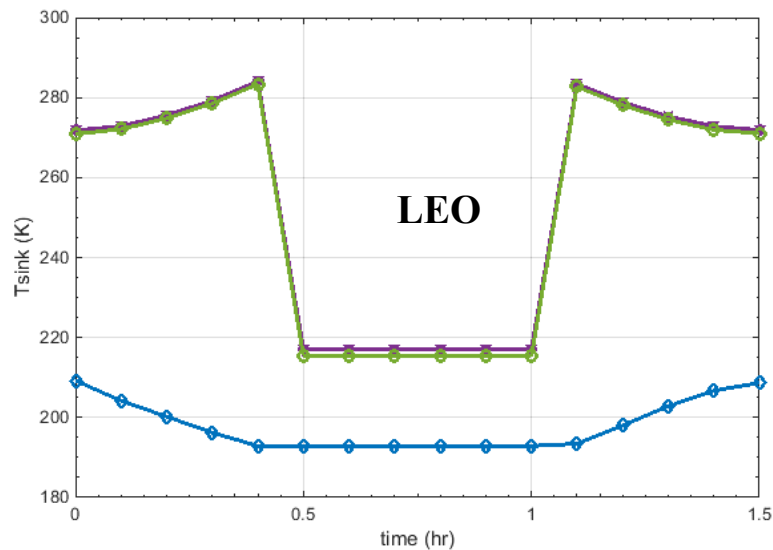


**LEO, altitude = 240 km, beta = 52°, +Z to Nadir, period = 1.488 hr**

**TLC, broadside to sun, inclination angle = 90°, period is 10 days**



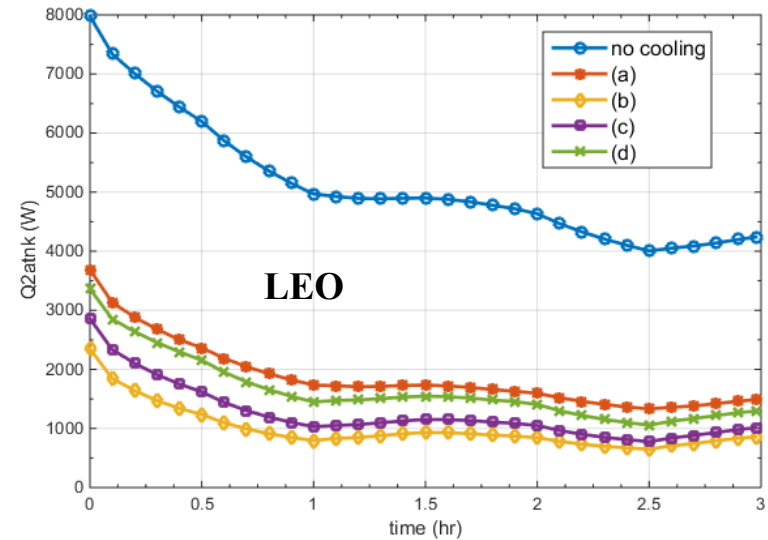
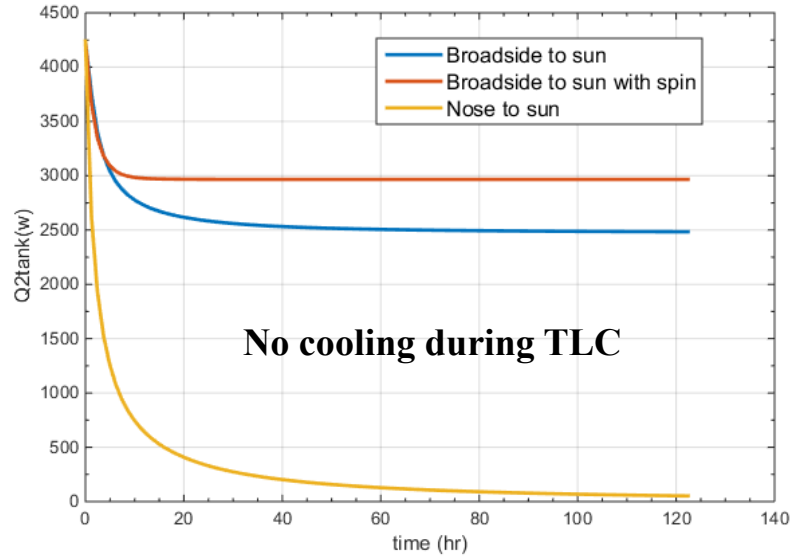
# Sink temperature at different locations on the forward skirt





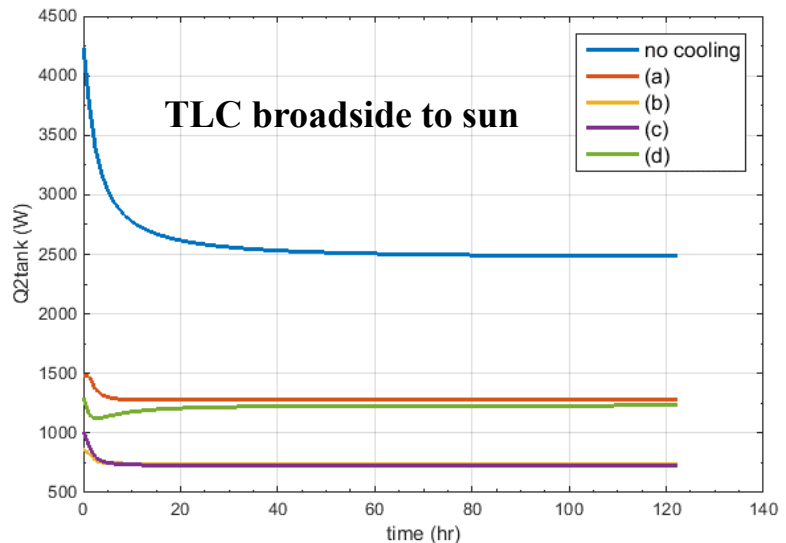


# Time history of Q2tank from forward skirt to LH2



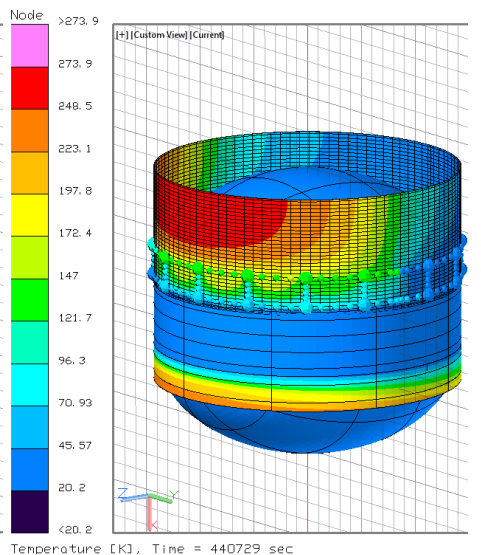
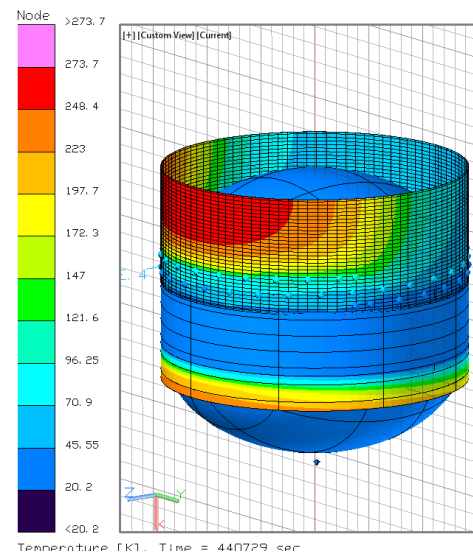
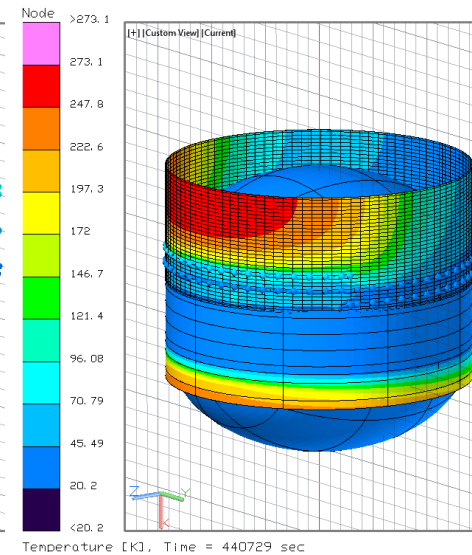
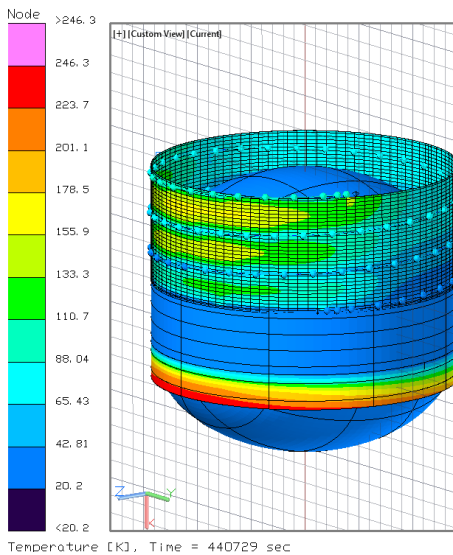
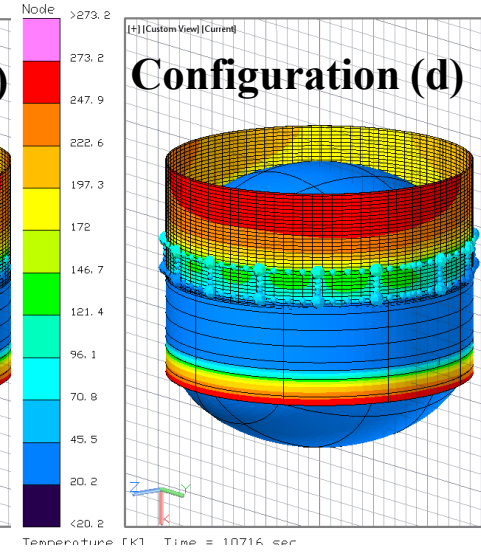
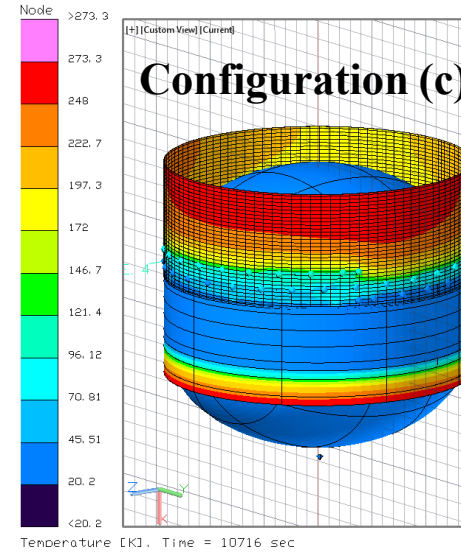
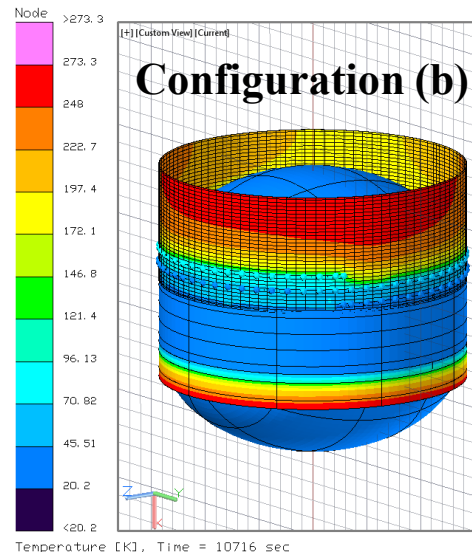
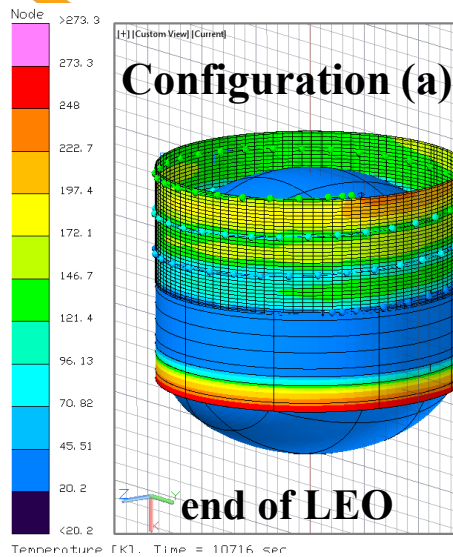
**For TLC,**

- **Nose to Sun is the coolest environment.**
- **Broadside to Sun with spin is the warmest.**
- **Broadside to Sun is considered for vapor cooling configurations performance.**
- **A constant vapor mass flow rate of 0.006 kg/s is used for all configurations.**





# Temperature distribution at different time



end of TLC



# Conclusions

- **3D model results showed similar cooling benefit to that indicated by 1-D model results**
- **Concentrating the cooling closer to skirt/tank connection appears to be more effective**
- **Multi-tube axial configuration not as effective as spiral tube**
- **Configurations B and C result in the least heat leak to the LH2 tank. Configuration C has lower pressure drop**
- **Vapor cooling will be more effective when the heat load is high on the structures**
- **For LEO, vapor cooling can reduce heat leak to the LH2 tank significantly**
- **For TLC nose to sun, vapor cooling might not save much heat leak to the LH2**



# Acknowledgements

- **Justin Elchert at GRC: valuable help on the TD model**
- **Douglas Bell at C & R tech: super tech support all the time**
- **Wesley Johnson and Lauren Best at GRC: review and technical input**
- **eCryo project: support of the work and travel to TFAWS**

